## *On the Drift of the Surface Material of Jupiter in different Latitudes.* By A. Stanley Williams.

The remarkable appearance presented by the great red spot on *Jupiter* in 1879 and subsequent years gave a great impetus to the physical observation of this planet. Notwithstanding, however, the numerous important investigations which resulted therefrom, and the many determinations of the period of rotation made from different markings in various latitudes, the question of the drift, or various rates of rotation, of the surface material in different latitudes still seems to be properly understood by only a very few. This is doubtless due in great measure to the fact that the chief investigations on the subject are scattered through the various publications of the years immediately following the apparition of the red spot, many of them not being very accessible, and that little has yet been done to bring together and adequately discuss the abundant existing material.

A great many determinations of rotation period in various latitudes were discussed by M. Belopolsky in a valuable paper published a few years ago,* the existence of the great equatorial current receiving full recognition. But, owing principally to the circumstance that a large number of results based on insufficient material were included in this discussion, the various minor, but yet very important, currents escaped notice.

In the present paper most of the chief thoroughly satisfactory determinations of rotation period are brought together and discussed under the heads of the different atmospheric currents to which they refer. The original sources of information have been referred to in nearly every case, and although it is probable that some first-class determinations may have been omitted, yet it is believed that all those contained in this paper are thoroughly to be relied upon. A good many results have been rejected from various causes; such as uncertainty as to the correct identification of the markings observed, or the short period of time over which the observations extend. And all determinations based solely upon positions derived from sketches have been rigidly excluded, experience having shown that such results are quite unreliable, except, possibly, in a few cases where the observations extend over very long periods of time.

In the present state of our knowledge there are nine distinct atmospheric currents recognisable upon *Jupiter*. Others will doubtless be added as our acquaintance with the planet becomes more intimate. But these nine currents are absolutely certain, and their boundaries are also well established within narrow limits, although it seems probable that, in some cases at least, these boundaries may vary slightly in position from time to time.

* "Ueber die Rotation des Jupiter," Mélanges mathématiques et astron. tirés du *Bulletin de l'Acad. impériale des Sciences de St.-Pétersbourg*, t. vii. 104.

With one exception the different atmospheric currents completely encircle the planet. They have therefore been arranged in zones, and numbered in order from north to south. After the number of the zone, or current, will be found the zenographical latitudes * of the north and south borders of the current. These limits are based chiefly upon my own observations and measures from 1879 to the present time, assisted by measured positions from photographs of *Jupiter* taken at the Lick Observatory. After the limits of latitude of each zone is the adopted average value of the period of rotation, R. This is not always the simple mean of the different results, and is to some extent a personal estimate of the average value. Lastly comes a complete list of the determinations of rotation period, with a short discussion of the results.

In these lists of determinations will be found :—(1) The year or years in which the observations on which the determination is based were made. (2) The period of rotation. (3) Some figures whereby some idea may be formed as to the degree of accuracy of the different results. A number followed by the letter *r* indicates the number of rotations of the planet elapsed between the first and last observations on which the period depends. A number followed by the letter *d* signifies the number of days covered by the observations. A number followed by the letter *s* gives the number of spots, where more than one was observed, the value of R in the second column being then the mean of the periods of these spots. It should be stated here that a rotation period based in this way upon several spots is much more to be relied upon for our purpose than is one derived from a single spot, however well observed. For in every zone of *Jupiter* the individual spots are found to have slightly different periods of rotation, showing that they have slight proper motions of their own. (4) The authority for the determination.

*Zone I.—Lat.* $+85°$ *to* $+28°$. $R=9^h\ 55^m\ 37^s.5$.

| | | | | |
|---|---|---|---|---|
| 1862 | $R = 9^h\ 55^m\ 25^s.7$ | 128r | Schmidt | *a* |
| 1880 | $32.5 \pm 0.77$ | 94r | O. Lohse | *b* |
| 1880 | $35.7$ | 2s | Hough | *c* |
| 1881 | $42.4 \pm 3.33$ | 159r | O. Lohse | *d* |
| 1888 | $40.8$ | 9s | Williams | *e* |
| 1892 | $38.9 \pm 1.20$ | 3s | „ | *f* |
| 1894–5 | $39.0$ | 2s | Denning | *g* |

*Notes.*—(*a*) Isolated dark spot in $+30°$. (*b*) Small dark spot in about $+34°$. (*c*) Two black spots on belt 2. (*d*) Bright spot in north polar cap. (*e*) Dark streaks extending from $+15°$ to $+70°$. (*f*) Dark streaks extending from $+40°$ to $+85°$. (*g*) Two black spots in about $+35°$.

* These have been derived by means of the table by Dr. O. Lohse, published in *Publicationen des Astrophysikalischen Observatoriums zu Potsdam*, No. 9, p. 7.

There is some evidence of a slight increase in the rate of rotation since 1862.

*Zone II.—Lat.* $+28°$ *to* $+24°$. $R = 9^h\ 54\frac{1}{2}^m$ *to* $9^h\ 56\frac{1}{2}^m$.

The region about the second dark belt north of the equator (the north temperate belt=belt No. 3 of Professor Hough and belt No. 4 of Dr. Terby) is certainly one of the most remarkable regions of the whole planet. Here in close juxtaposition have been found both the quickest and the slowest of the great Jovian atmospheric currents. Zone II. occupies the northern half of the above-mentioned belt, and includes also the greater part of the light region intervening between it and the next dark belt to the north. Usually the drift of the surface material in Zone II. appears to differ little from that indicated by the red spot. For instance, in 1888 a number of dark streaks were visible having a north and south direction, and extending from N. lat. 60°–70° uninterruptedly across the zone. The mean value of R from nine of these streaks was $9^h\ 55^m\ 40^s{\cdot}8$, as given under Zone I. Some dark spots on the north temperate belt itself also rotated at a similar rate. But in the apparition of 1891–92 the region of this belt was in an abnormally disturbed state. A large protuberant mass on the north side of the belt was then observed to rotate for a time in a period of $9^h\ 54^m\ 31^s$.* In the succeeding opposition of *Jupiter* a great many spots, both light and dark, were visible on the north side of the belt. These had rotation periods considerably longer than that of the red spot. The exact average rate of rotation at this time is uncertain at present, as there were considerable variations in the case of different spots, and the observations, which are numerous, have only as yet been partially reduced. It cannot, however, well be shorter than the value, $9^h\ 56\frac{1}{2}^m$, stated above. Shortly, then, the facts in connection with this zone are as follows:—Usually the drift of the surface material is almost exactly at the same rate as the red spot. But at times, when the region is in a disturbed state, the rotation period may be as short as $9^h\ 54\frac{1}{2}^m$, or as long as $9^h\ 56\frac{1}{2}^m$. Both rates are given in the little table at the end of this paper; the latter in order to emphasise the enormous contrast at times existing between the velocity of the surface drift in this zone and in the adjacent Zone III.

*Zone III.—Lat.* $+24°$ *to* $+20°$. $R = 9^h\ 48^m$ *to* $9^h\ 49\frac{1}{2}^m$.

In 1880 and again in 1891 an eruption of dark spots broke out on the south edge of the north temperate belt. These spots had a rapid movement from east to west compared with all other objects. The exact rate of rotation in 1880 is uncertain, but appears to have been about $9^h\ 48^m$. The observations, which

* Some particulars about this spot will be found in the *Observatory*, 1892, p. 112.

are numerous, are scattered through the publications of the time, and have never yet been properly discussed. Doubtless, as in 1891, the individual spots differed considerably amongst themselves as regards their rate of motion.

Some account of the disturbance of 1891 will be found in the *Observatory*, 1892, pp. 109–112, and also in a letter by Mr. Denning on p. 147 of the same periodical. Shortly it may be stated that the average rotation period was about $9^h\ 49\frac{1}{2}^m$, but that there were considerable differences in the rate of motion of the individual spots, and that in more than one instance sudden changes of considerable amount occurred in the velocities of some of these spots. It is a matter of great importance to determine whether this enormously swift current of Zone III. is a permanent current, or only a temporary one arising when the region is in a state of unusual disturbance. In the succeeding opposition of 1892, although the disturbance had in great measure subsided, yet a number of minute black spots were still visible on the south edge of the belt, and these moved with much the same velocity as the spots of the previous year had done. This would imply considerable permanence at least in this atmospheric current.

The great contrast between the velocity of the surface drift in the two adjacent Zones II. and III. has already been alluded to when treating of the former zone. Taking the extreme values, the difference of velocity amounts to close on 400 miles (644 kilometres) per hour. Why this enormous difference should exist between the velocities of two comparatively narrow atmospheric currents lying side by side in almost the same north latitude is a mystery at present, like so many others of the phenomena of *Jupiter*. Of the certainty of the fact, however, there is no doubt, and it must be taken into account in every theory of the planetary constitution.

*Zone IV.—Lat.* + 20° *to* + 10°. *R.* = $9^h\ 55^m\ 33^s{\cdot}9$.

| | h m s | s | |
|---|---|---|---|
| 1787 | R=9 55 33·6 | 242r | Schroeter |
| 1835 | 21·3 | 225r | Airy (from obs. by Glaisher) |
| 1835 | 25·5 ± 0·17 | 2s | Beer and Mädler |
| 1866 | 18·3 | 138r | Schmidt |
| 1881 | 35·2 ± 0·85 | 166r | O. Lohse |
| 1887 | 34·5 | 2s | Terby |
| 1887 | 36·5 | 17s | Williams |
| 1888 | 40·9 | 18s | ,, |
| 1890 | 34·5 | 5s | Hough |
| 1890–1 | 38·3 | 831r | Denning |
| 1891 | 27·4 | 119d | Hough |
| 1894–5 | 35·0 | 9s | Denning |

The markings observed consist of white and dark spots on the north side of the north equatorial belt and in the bright zone separating that belt from the north temperate belt. On the whole the agreement between the different results is close and satisfactory. It is certain, too, that some of the differences are due to real slight variations in the velocity of the drift. There seems, however, to have been no permanent sensible change in this velocity since the first determination by Schroeter in 1787.

*Zone V.—Lat.* + 10° *to* — 12°. *R* = $9^h\ 50^m\ 20^s$.

| | h m s | s | | |
|---|---|---|---|---|
| 1879 | R=9 49 59 | | 256r | O. Lohse |
| 1879–80 | 50 3·5 | | 302d | Hough |
| 1880 | 50 8·4 | ±0·22 | 504r | O. Lohse |
| 1880 | 50 0 | | 78r | Schmidt |
| 1880 | 49 53·5 | | ... | Kortazzi |
| 1880 | 50 4·5 | | 2s | Denning |
| 1880–1 | 5 | | ... | " |
| 1880–1 | 6·6 | | 89d | Marth (from obs. by several observers) |
| 1880–1 | 7 | | 55d | Kortazzi |
| 1880–1 | 5·1 | | 2s | Hough |
| 1881 | 10·7 | ± 1·78 | 127r | O. Lohse |
| 1880–2 | 7·42 | | ... | Marth (from obs. by several observers) |
| 1880–2 | 9·8 | | ... | Hough |
| 1881–2 | 9·8 | | 252d | " |
| 1882–3 | 9·8 | | ... | " |
| 1882–3 | 9·6 | | ... | Denning |
| 1880–5 | 9·84 | | ... | Marth (from obs. by several observers) |
| 1882–4 | 12·25 | | ... | Marth (from obs. by several observers) |
| 1883–4 | 12·7 | | ... | Hough |
| 1883–4 | 12·1 | | ... | Denning |
| 1884–5 | 8·2 | | 261d | Hough |
| 1885 | 14·34 | | ... | Denning |
| 1885 | 15·88 | | ... | Marth (in his ephemeris for 1886–7) |
| 1886 | 22·9 | | 112r | Williams (from obs. by Denning) |
| 1887 | 22·4 | | 21s | Williams |
| 1888 | 30·0 | | 2s | Marth (from obs. by Williams) |
| 1888 | 34·3 | | 275r | Williams |
| 1891 | 26·4 | | 99l | Hough |

This zone is the zone of the great equatorial current, which was discovered by Cassini in the latter part of the seventeenth century. The determinations of the value of R since the time of this astronomer have been very numerous, as will be seen from the foregoing list. One of the most remarkable circumstances revealed by this list is the continual increase in the length of the period of rotation, amounting in ten years to about half a minute of time. At present the period seems to be still longer, the average duration for the whole zone being now probably about $9^h\ 50^m\ 40^s$. A new determination during the present opposition, based on observations of as many spots as possible, is much to be desired.

All the results contained in the above list refer to spots situated on the south side of the equator. Usually the markings lying on the north side of the equator have rotated at nearly the same rate as those situated south of the equator, but in 1887 the former rotated somewhat more slowly than the latter, and the same thing seems to have occurred in 1882. This will be seen from the following determinations of rotation period from spots lying on the north side of the equator, compared with those for corresponding years in the previous list.

| | h m s | | |
|---|---|---|---|
| 1882 | R = 9 51 40 | 27d | Denning |
| 1884-5 | 50 9·2 | 238d | Hough |
| 1887 | 50 40·1 | 5s | Williams |
| 1891 | 50 31·6 | 69d | Hough |

*Zone VI.—Lat.* − 12° *to* − 18°. $R = 9^h\ 55^m\ 40^s$.

The great equatorial current of Zone V. extends so far south as usually to include at least one half of the south equatorial belt. This belt is generally double, appearing composed of two dark bands separated by a narrow clear interval. The material of the southernmost component appears, however, usually to rotate at about the same rate as the red spot. The great bay in the south equatorial belt opposite the latter is well known. This, however, in itself, would not prove that the material of the belt rotates at the same rate as the spot. The following results show, however, that the surface material did rotate at approximately the same rate as the red spot in the under-mentioned years.

| | h m s | | |
|---|---|---|---|
| 1877 | R = 9 55 40·5 | 567r | Trouvelot |
| 1877-9 | 36·7 | 2076r | " |
| 1884-5 | 43·5 | 2s | Hough |

*Zone VII.—Lat.* − 14° *to* − 28°. $R = 9^h\ 55^m\ 40^s$.

This zone comprises the great red spot, and is really only part of a zone, since it is confined to a comparatively small region

of little more than 36° of longitude in extent. All the rest of the surface south of the south equatorial belt, and in the same latitude as the red spot, is comprised in the succeeding Zone VIII. The determinations of the rotation period of the red spot are very numerous and well known, and it is unnecessary to give them here.

*Zone VIII.—Lat.* − 18° *to* − 37°. $R = 9^h\ 55^m\ 18^s{\cdot}1$.

| | | | |
|---|---|---|---|
| | h m s s | | |
| 1787 | R=9 55 17·6 | 250r | Schroeter |
| 1862 | 17·2 | 128r | Schmidt |
| 1872–3 | 19·6 ± 2·34 | ... | O. Lohse |
| 1880 | 16·18 | ... | Barnard |
| 1880–1 | 17·9 | ... | Denning |
| 1880–1 | 19·07 | ... | Barnard |
| 1887 | 18 | 55d | Terby |
| 1887 | 17·1 | 3s | Williams |
| 1889 | 16·7 ± 0·33 | 263r | " |
| 1889 | 19·0 ± 0·26 | 326r | " |
| 1890–1 | 18·3 | 1296r | Denning |
| 1891 | 18·2 | 53r | " |
| 1891 | 20 | 2s | Hough |

The drift of the surface material has been remarkably uniform in this zone, no material change having taken place since the first determination by Schroeter more than 100 years ago. In fact this atmospheric current is undoubtedly the most steady one of which we have any record. Most of the results contained in the above list relate to markings in about −30°. The first determination of 1889 relates, however, to a dark spot in the northernmost part of the zone, and having a dark streak extending southwards to about lat. −28°. Many unpublished observations by the writer of white spots in the bright zone south of the south equatorial belt show that the white surface material of this region has a similar motion. In the midst of this atmospheric current the great red spot emerges, as it were, like an island in a river.

*Zone IX.—Lat.* − 37° *to* − 55°. $R. = 9^h\ 55^m\ 5^s$.

| | | | | |
|---|---|---|---|---|
| | h m s s | | | |
| 1886 | R=9 55 11·14 | ... | Young | *a* |
| 1888 | 0·9 ± 0·97 | 2s | Williams | *b* |
| 1890 | 6·7 ± 0·21 | 280r | " | *c* |

*Notes.*—(*a*) Small white spot in lat. 50° south. (*b*) Lat. −37° to −55°. (*c*) Lat. −36° to −47°.

M

The existence of this comparatively swift current so far south is a rather curious anomaly. The drift of the material near the south pole still remains to be ascertained, and the anomalous nature of this current renders it important to solve this question.

*Summary of Zones.*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | h m | s | | h m |
| Zone | I. | Lat. +85° to +28° | R = | 9 55 | 37·5 | | |
| „ | II. | +28 „ +24 | | 9 54½ | | to | 9 56½ |
| „ | III. | +24 „ +20 | | 9 48 | | to | 9 49½ |
| „ | IV. | +20 „ +10 | | 9 55 | 33·9 | | |
| „ | V. | +10 „ −12 | | 9 50 | 20 | | |
| „ | VI. | −12 „ −18 | | 9 55 | 40 | | |
| „ | VII. | −14 „ −28 | | 9 55 | 40 | | |
| „ | VIII. | −18 „ −37 | | 9 55 | 18·1 | | |
| „ | IX. | −37 „ −55 | | 9 55 | 5 | | |

Zone VII. is incomplete, being confined to the red spot.

A glance at the above table, in which the results for the different zones are summarised, will show how anomalous and unsymmetrical are most of the currents. In particular, the northern hemisphere differs altogether from the southern hemisphere. In the latter the very remarkable region about lat. + 25° is absent altogether. Possibly the presence of the great red spot may have had something to do with this. On the other hand, the northern hemisphere lacks the red spot and the two moderately swift currents of Zones VIII. and IX., the surface drift being nearly uniform from lat. + 28° almost to the pole.*

One of the most remarkable peculiarities about these atmospheric currents of *Jupiter*, is that they circulate in a due east and west direction, and show little or no sign of movement toward or from the poles. They appear also to be usually sharply bounded, one current by another, without indication of a gradual transition from one to another, though there are exceptions to this rule. Any circulation in a north and south direction would seem to take place chiefly by means of the narrow rifts and streamers seen to traverse obliquely some of the belts and clear zones of *Jupiter*. But this subject has only just begun to be investigated by students of the planet.

It has sometimes been stated that *Jupiter* has a certain amount of resemblance to the Sun, inasmuch as in both orbs the rotation is most rapid near the Equator. I have therefore added the following table in which the solar rotation period, as com-

* A difference of one minute in the period of rotation of two currents near *Jupiter's* equator signifies a real difference of 45 miles (72 kilometres) per hour in the velocities of such currents.

puted by Spoerer's formula,* is given for the latitudes corresponding to the centres of the different zones of *Jupiter*. The rotation periods for both orbs are also expressed in terms of that for their respective equatorial zones, as this will bring out better the *relative* drifts of the solar and jovian currents :—

| Latitude. | *Jupiter.* Rotation period for different latitudes In time. | In terms of the Equatorial period. | *The Sun.* Rotation period for different latitudes In days. | In terms of the Equatorial period. |
|---|---|---|---|---|
| ° | h m s | | d | |
| +46 | 9 55 37·5 | 1·0089 | 28·625 | 1·1407 |
| +26 | 9 54 30 | 1·0071 | 26·165 | 1·0427 |
| | 9 56 30 | 1·0104 | | |
| +22 | 9 48 45 | 0·9973 | 25·855 | 1·0303 |
| +15 | 9 55 33·9 | 1·0089 | 25·445 | 1·0140 |
| 0 | 9 50 20 | ... | 25·094 | ... |
| −15 | 9 55 40 | 1·0090 | 25·445 | 1·0140 |
| −21 | 9 55 40 | 1·0090 | 25·786 | 1·0276 |
| −27½ | 9 55 18·1 | 1·0084 | 26·295 | 1·0478 |
| +46 | 9 55 5 | 1·0081 | 28·625 | 1·1407 |

## *Ephemeris for Physical Observations of the Moon*, 1896.
By A. Marth.

| Greenwich Noon. | Selenographical Colong. of the Sun. | Lat. | Geocentric Libration. Sel. Long. of the Earth. | Lat. | Combined Amount. | Direction. |
|---|---|---|---|---|---|---|
| 1896. | ° | ° | ° | ° | ° | ° |
| Jan. 19 | 321·23 | −0·91 | −0·55 | −1·80 | 1·88 | 163·0 |
| 20 | 333·41 | 0·89 | 1·77 | 3·09 | 3·61 | 150·2 |
| 21 | 345·58 | 0·87 | 3·15 | 4·25 | 5·29 | 143·5 |
| 22 | 357·74 | 0·85 | 4·43 | 5·24 | 6·86 | 139·9 |
| 23 | 9·90 | 0·83 | 5·51 | 6·02 | 8·15 | 137·7 |
| 24 | 22·05 | 0·81 | 6·31 | 6·53 | 9·07 | 136·2 |
| 25 | 34·20 | −0·78 | −6·76 | −6·75 | 9·54 | 135·2 |
| 26 | 46·34 | 0·76 | 6·80 | 6·62 | 9·48 | 134·4 |
| 27 | 58·48 | 0·73 | 6·43 | 6·13 | 8·87 | 133·8 |
| 28 | 70·62 | 0·70 | 5·64 | 5·27 | 7·71 | 133·2 |
| 29 | 82·75 | 0·67 | 4·49 | 4·05 | 6·04 | 132·1 |
| 30 | 94·87 | 0·64 | 3·06 | 2·55 | 3·98 | 129·8 |
| 31 | 106·00 | −0·61 | −1·47 | −0·88 | 1·71 | 120·9 |

* Daily angular rotation: $\xi = 8^\circ{\cdot}548 + 5^\circ{\cdot}798$ cos latitude. *Publ. des Astrophysik. Obser. zu Potsdam*, Band x. p. 145. [I am indebted to Mr. E. W. Maunder for the above Table.]